ABUNDANCE PATTERNS OF HEAVY ELEMENTS IN DAMPED LYMAN-ALPHA GALAXIES

Varsha P. Kulkarni [1,2] and S. Michael Fall

Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, U.S.A.

and

J. W. Truran [3]

Department of Astronomy & Astrophysics, University of Chicago,

5640 S. Ellis Ave.,Chicago, IL 60637, U.S.A.

Received ______________________; accepted ______________________

[1]Also, Department of Astronomy & Astrophysics, University of Chicago, 5640 S. Ellis Ave.,Chicago, IL 60637, U.S.A.

[2]Current Address: Steward Observatory, University of Arizona, Tucson, AZ 85721, U.S.A.

[3]Also, the Enrico Fermi Institute

ABSTRACT

We present a quantitative analysis of the abundances of heavy elements in damped Lyα galaxies in the sample of Lu et al. (1996). In particular, we compare the observed gas-phase abundances with those expected when the intrinsic (i.e., nucleosynthetic) pattern is the same as that in either the Sun or in Galactic halo stars and when the depletion pattern is the same as that in the warm Galactic interstellar medium, but with various values of the dust-to-metals ratio. We find that the observations are equally consistent with the solar and halo-star intrinsic patterns and that they favor some depletion, the typical dust-to-metals ratio being 40% – 90% of that in the Milky Way today. However, neither intrinsic pattern matches the observations perfectly. For the solar pattern, the discrepancy is mainly with [Mn/Fe], while for the halo-star pattern, the discrepancy is with [Zn/Fe], [Ni/Fe], and possibly [Al/Fe]. Our analysis does not support the claim by Lu et al. that the damped Lyα galaxies have halo-star abundance patterns and no dust depletion.

Subject headings: galaxies: abundances — galaxies: evolution — galaxies: quasars: absorption lines

1. INTRODUCTION

The abundances of heavy elements in damped Lyα (DLA) galaxies provide important clues about the histories of metal production and star formation in these objects (Lanzetta, Wolfe, & Turnshek 1995; Pei & Fall 1995; Timmes, Lauroesch, & Truran 1995). Many of the observational studies to date have focussed on Zn and Cr (Pettini et al. 1997, and references therein). These elements track Fe almost perfectly in Galactic stars with $-3 \lesssim$ [Fe/H] $\lesssim 0$ (see, e.g., Wheeler, Sneden, & Truran 1989). Since Zn is relatively undepleted while Cr is strongly depleted in the Galactic interstellar medium (ISM) (e.g., Savage & Sembach 1996), [Zn/H] should be a reliable indicator of the metallicity and [Cr/Zn] should be an indicator of the dust content. Measurements of Zn and Cr show that the typical metallicity and dust-to-gas ratio in DLA galaxies at $\bar{z} \approx 2$ are $\sim 1/10$ the corresponding values in the local ISM (Pettini et al. 1994). The low dust-to-gas ratio is also consistent with the mild preferential reddening of quasars with DLA galaxies in the foreground (Pei, Fall, & Bechtold 1991). These results suggest that the typical dust-to-metals ratio has remained roughly constant (to within factors of 2 or so) since $z \approx 2$, and that the dust is produced in step with the metals.

Lu et al. (1996) recently obtained high-resolution, high-S/N spectra of 14 DLA galaxies using the Keck Telescope. Combining these and similar observations of nine DLA galaxies from the literature, they concluded that the DLA galaxies have the nucleosynthesis pattern expected purely from Type II supernovae, similar to that found in Galactic halo stars, and show no evidence of dust depletion. However, as we show in this Letter, the Lu et al. interpretation is not unique. The main reason for this is that the differences in the relative abundances caused by Type I and Type II supernovae are comparable to the differences caused by even small amounts of dust depletion. We demonstrate this explicitly by comparing the observed relative abundances of different pairs of elements

with the values expected for different assumptions about the nucleosynthesis pattern and the dust-to-metals ratio. Our conclusions are similar to those reached by Lauroesch et al. (1996), who considered an earlier set of data on many different elements, and Pettini et al. (1997), who considered a homogeneous set of data on Zn and Cr.

2. METHOD AND RESULTS

To derive the expected relative gas-phase abundances in terms of the dust-to-metals ratio, we start with the basic equation that relates the abundances of atoms of any element X in the gas and solid phases (X^{gas} and X^{sol}) to the total abundance ($X^{tot} = X^{gas} + X^{sol}$). We assume that the relative total abundance of any two elements X and Y is the same as that in a known reference pattern, which may be chosen later to be either the solar pattern or the halo-star pattern, i.e.,

$$X^{tot}/Y^{tot} = (X^{tot}/Y^{tot})_{ref}. \tag{1}$$

Next, we assume that the DLA galaxies have the same relative dust-depletion pattern, i.e., the same composition of dust grains, as a reference ISM and differ only in the absolute number of dust grains per unit mass of the ISM. This gives

$$X^{sol}/Y^{sol} = (X^{sol}/Y^{sol})_{ref}, \tag{2}$$

and hence,

$$\frac{X^{gas}}{Y^{gas}} = \frac{(X^{tot}/Y^{tot})_{ref} - (Y_{sol}/Y_{tot})(X^{sol}/Y^{sol})_{ref}}{1 - (Y_{sol}/Y_{tot})}. \tag{3}$$

For simplicity, we take the reference depletion pattern to be that in the Galactic ISM and assume that the total abundance of each element in the Galactic ISM equals the solar abundance. [4] Denoting the gas-phase abundances, relative to the solar abundances, of X

[4]Some recent observations indicate nonsolar abundances in the Galactic ISM. However,

and Y in the Galactic ISM as $\Delta_{X\,G} = (X^{gas}/H)_G/(X/H)_\odot$ and $\Delta_{Y\,G} = (Y^{gas}/H)_G/(Y/H)_\odot$, we can now reexpress equation (3) in the form

$$\frac{X^{gas}}{Y^{gas}} = \frac{(X^{tot}/Y^{tot})_{ref} - (R/R_G)_Y (X/Y)_\odot (1 - \Delta_{X\,G})}{[1 - (R/R_G)_Y (1 - \Delta_{Y\,G})]}, \tag{4}$$

where

$$(R/R_G)_Y \equiv (Y^{sol}/Y^{tot})/(Y^{sol}/Y^{tot})_G = (Y^{sol}/Y^{tot})/(1 - \Delta_{Y\,G}) \tag{5}$$

denotes the dust-to-metals ratio of Y relative to that in the Milky Way. We use the notation [X/Y] to represent $\log\{(X^{gas}/Y^{gas})/(X/Y)_\odot\}$ in DLA galaxies. In the following, we take the reference element Y to be Fe or Zn, since these have both been used as metallicity indicators for DLA galaxies (although Fe has the serious disadvantage that it depletes easily onto dust grains). The dust-to-metals ratio for any other element Y is related to the dust-to-metals ratio for Fe by the relation $(R/R_G)_Y = (R/R_G)_{Fe}(Y/Fe)_\odot/(Y^{tot}/Fe^{tot})_{ref}$. Since the halo-star abundances of Zn, Cr, and Ni relative to Fe are very close to the solar values for $-3 \lesssim$ [Fe/H] $\lesssim -1$, we have $(R/R_G)_{Zn} = (R/R_G)_{Fe}$ for both the halo-star and the solar intrinsic abundance patterns (and similarly for Cr or Ni). We therefore use the symbol R/R_G to denote $(R/R_G)_{Zn}$ and $(R/R_G)_{Fe}$. Equation (4) shows that the gas-phase abundances with respect to Fe or Zn are determined by R/R_G alone.

In this Letter, we focus on the abundances of S, Si, Al, Zn, Fe, Cr, Ni, and Mn. [5] For each of these elements, we choose the input quantities in equation (4) as follows. We

---

since these results are not yet definitive and may be caused by purely local effects (Savage & Sembach 1996), we continue to adopt the solar values.

[5] We do not use N and O because very few reliable measurements exist for these elements due to problems of line saturation and blending with the Lyα forest. The existing measurements also show a large scatter in [N/O] (Green et al. 1995; Lu et al. 1996; Molaro et al. 1996).

adopt the solar abundances from Anders & Grevesse (1989). For the relative halo-star abundances $[X/Zn]_{halo}$ or $[X/Fe]_{halo}$, we use the following values: +0.4 dex for Si and S; -0.3 dex for Al; -0.25 dex for Mn; 0.0 dex for Cr, Ni, Fe, and Zn. These are representative values based on observations of Galactic halo stars with $-3 \lesssim$ [Fe/H] $\lesssim -1$ (see, e.g., Gratton & Sneden 1987, 1988, 1991; Magain 1989; Ryan, Norris, & Bessell 1991; Sneden, Gratton, & Crocker 1991; McWilliam et al. 1995; Ryan, Norris, & Beers 1996). Our assumed value for Al is perhaps the least certain, since the abundance of this element shows considerable scatter in halo stars. For the Galactic depletions Δ_{XG}, we adopt the values observed in the warm, diffuse ISM, since these seem appropriate for comparison with the DLA galaxies, which in most cases show almost no detectable H_2 [Levshakov et al. 1992; but see Ge & Bechtold 1997 for a case with relatively high $f(H_2)$]. For S, Mn, Cr, Si, Fe and Ni, we adopt the warm disk Galactic depletions from Table 6 of Savage & Sembach (1996). For Zn, we use $\log \Delta_{X\,G} = -0.20$ (Roth & Blades 1995; Sembach et al. 1995), and for Al, we use $\log \Delta_{X\,G} = -1.16$ (Barker et al. 1984, corrected for the revised oscillator strength from Morton 1991). The value for Al is somewhat uncertain because of line saturation effects.

We now compare the predictions from equation (4) with the data for the 23 DLA galaxies from Table 16 of Lu et al. (1996). These absorbers have $0.7 \leq z \leq 4.4$ and $20.0 \leq \log N_{\rm HI} \leq 21.7$. Unfortunately, simultaneous measurements of more than three elements exist for only a third of these objects. Hence, we exploit the relatively large sample to infer the typical abundance pattern in DLA galaxies rather than the pattern in any particular system. In Figures 1 and 2, we plot the logarithmic gas-phase abundances of S, Mn, Cr, Si, Fe (or Zn), Ni, and Al, relative to Zn or Fe, in increasing order of condensation temperature. Following Lu et al., we assume that the absorbers are mostly neutral. In both Figures, the upper panels are scaled to the solar abundances [i.e., $(X^{tot}/Y^{tot})_{ref} = (X/Y)_{\odot}$], while the lower panels are scaled to the halo-star abundances [i.e., $(X^{tot}/Y^{tot})_{ref} = (X^{tot}/Y^{tot})_{halo}$]. The light vertical segments show the full range of

the actual measurements for the DLA galaxies. The heavy filled circles and vertical bars show the medians of the observations (including upper and lower limits) and the standard errors in the medians (see, e.g., Sachs 1984). These errors may be underestimates in some cases, since they include only the statistical, not the measurement, uncertainties (which are typically ± 0.15 dex or less). We consider the medians rather than the means because the sample is small, and because they allow the use of limits as well as actual measurements. This procedure works in most cases because the element ratios are available for at least three absorbers and typically many more. However, the ratios [S/Zn], [S/Fe], [Al/Zn], [Al/Fe], and [Mn/Zn] are available for fewer than three absorbers, not enough to compute reliable median values. Therefore, for these, we show the individual measurements with open circles and the upper or lower limits with open triangles.

The lines in Figures 1 and 2 represent the expected gas-phase abundances for different assumed values of the dust-to-metals ratio: $R/R_G = 0$ (light horizontal lines), 0.3 (short-dashed lines), 0.6 (long-dashed lines), and 0.9 (dot-dashed lines). In both Figures, we have assumed a solar intrinsic pattern in the top panels and a halo-star-like intrinsic pattern in the bottom panels. If DLA galaxies possessed no dust, as argued by Lu et al. (1996), then the observed relative abundances for all elements would lie close to the light horizontal line in each Figure. Clearly, this is not the case. Based on a Kolmogorov-Smirnov test, the observed deviation in Figure 1 from the case of zero dust is significant at the level of $> 99\%$ with or without the inclusion of S and Mn. For Figure 2, the significance of the deviation is $\approx 99\%$ including S and Al and $\approx 97\%$ excluding them. Thus, we find evidence for dust depletion irrespective of whether the intrinsic abundances are assumed solar or halo-star-like. The solar pattern with $R/R_G \approx 0.4 - 0.9$ is roughly consistent with the observations of most of the elements. This range of R/R_G agrees nicely with the result of

Pettini et al. (1997) based on Zn and Cr alone. [6]

Closer inspection shows that a single value of R/R_G cannot simultaneously fit the observations of all the elements. For example, in Figure 1*b*, S and Si cannot be fitted at all. In Figure 2*a*, Mn is the only discrepant element. There is no discrepancy for Ni in the sense that there is for Mn, because the fit for the former improves as the dust-to-metals ratio increases. The discrepancy for [Mn/Fe] is the main point used by Lu et al. (1996) to argue that DLA galaxies are dust-free. However, since Mn and Fe are both strongly depleted even in the warm Galactic ISM, they are less reliable indicators of the dust content than are Zn and Mn, or Zn and Fe, or Zn and Cr. In fact, from Figure 1, the data for [Mn/Zn] and [Fe/Zn] both require some dust depletion. In Figure 2*b*, Zn and Ni require more depletion compared to S, Mn, and Si, while Al cannot be fitted at all. This is difficult to reconcile with a purely halo-star abundance pattern with no dust. We have also performed calculations with a depletion pattern similar to that in cold clouds in the Galactic ISM and find that it also fails to give simultaneous agreement for all elements, for solar or halo-star abundance patterns. This suggests that the dust depletion pattern in DLA galaxies may differ from that in the Galactic ISM . In any case, we conclude that dust depletion can easily mask or confuse the underlying nucleosynthetic pattern, in agreement with the suggestion by Lauroesch et al. (1996).

---

[6] However, our estimates of the typical metallicity and dust-to-gas ratio in the DLA galaxies from the Lu et al. (1996) sample are $\approx 1/10 Z_\odot$ and $\approx 1/15$ of the Galactic value (Kulkarni 1996), i.e., $\approx 1.5 - 2$ times higher than the estimates by Pettini et al. (1997). This slight difference arises because we have included the weak depletion of Zn (≈ 0.2 dex) in the warm Galactic ISM, while Pettini et al. have not.

3. DISCUSSION

The evidence presented here that the DLA galaxies at $z \approx 2 - 4$ contain small but significant amounts of dust is consistent with several other observations. These include the mild reddening of quasars with DLA galaxies in the foreground (Pei et al. 1991) and the mild depletion of Cr relative to Zn in DLA galaxies (Pettini et al. 1994, 1997). Another relevant observation is that, in most cases, the DLA galaxies emit weakly if at all in the Lyα line (Lowenthal et al. 1995 and references therein). This is also true of the starburst galaxies found at $z \approx 3$ by Steidel et al. (1996), which would almost certainly be classified as DLA galaxies, if they could be observed in absorption. The simplest explanation for these observations is that Lyα photons are produced within the galaxies (in the recombinations following H ionization by young stars and other sources) but are subsequently absorbed by dust grains before escaping. There are other possibilities, but they involve either special viewing angles or times and would not apply to a population of randomly oriented galaxies of various ages (Charlot & Fall 1993, and references therein).

The presence of some dust in DLA galaxies is certainly plausible. Dust is produced in the cool envelopes of intermediate-mass stars and in the dense shells of supernova remnants, although it is not clear how long it survives once it enters the ISM (which depends on the unknown intensity of the ultraviolet radiation field, frequency of shocks, and so forth). Similarly, it seems reasonable that the DLA galaxies have neither purely solar nor purely halo-star abundance patterns. The DLA galaxies at $z \approx 2$ are 1–2 Gyr older than those at $z \approx 4$, a range in ages probably sufficient to include enrichment by both Type I and Type II supernovae. The large scatter in the metallicities of the DLA galaxies at each redshift (a factor of $\approx 15 - 30$ as measured by [Zn/H] or [Fe/H]) also indicates that they are observed in very different stages of chemical evolution and therefore that they could be expected to exhibit a mixture of both solar and halo-star abundance patterns. We note, however, that

DLA galaxies with the highest metal and hence dust content tend to be underrepresented in samples derived from optically selected quasars (Fall & Pei 1993).

Lu et al. (1996) reached different conclusions because they disregarded Zn as a metallicity indicator. As we have already emphasized, the rationale for choosing Zn is that it tracks Fe almost perfectly in Galactic stars over a wide range of metallicities and is nearly undepleted in the Galactic ISM. In contrast, Fe, the metallicity indicator preferred by Lu et al., is highly depleted in the Galactic ISM. As justification for ignoring Zn, Lu et al. appealed to theoretical models of Type II supernovae by Woosley & Weaver (1995), which, in their present form, do not reproduce the observed ratio [Zn/Fe] ≈ 0 in Galactic halo stars (see also Hoffman, Woosley, & Qian 1997). This immediately raises the question of how accurate the models are in predicting the relative abundances of Zn and Fe. Woosley & Weaver (1995) point out major uncertainties associated with the position of the mass cut, the time between stalling of the prompt shock and neutrino reheating, and the electron distribution in the innermost ejected layers. It has also been suggested that significant amounts of ^{64}Zn are synthesized in neutrino-driven winds during the explosions, but the corresponding yields have so far only been calculated schematically (Hoffman et al. 1996, 1997). Given these uncertainties in the models, it is not clear that there is a significant discrepancy between the predicted and observed values of [Zn/Fe] in metal-poor stars. In any case, we see no reason to treat Zn as an anomalous element and no reason to assume that the intrinsic abundance of Zn relative to Fe in the DLA galaxies differs from that in the Milky Way.

To make further progress in discerning the intrinsic nucleosynthesis pattern in DLA galaxies, it is critical to obtain observations of several weakly depleted elements in the same objects. (Conversely, a comparison between weakly and strongly depleted elements is required to determine the dust depletion pattern.) In principle, N and O are a suitable

pair, since they are both weakly depleted in the Galactic ISM. The problem in this case is that the nucleosynthesis of N is not fully understood. Observations of halo stars show considerable scatter in [N/O] over the metallicity range -2.5 $\lesssim$ [Fe/H] $\lesssim$ -0.6 dex, with an average ratio [N/O] $\approx$ -0.2 dex (Laird 1985; Carbon et al. 1987). Furthermore, there are uncertainties in the relative importance of primary and secondary production of N at low metallicities. Significant primary production of N may occur in low-metallicity, massive stars (Timmes, Woosley, & Weaver 1995). These uncertainties cast some doubt on the use of [N/O] as a tool for probing the early nucleosynthesis history of DLA galaxies. S and Zn are potentially more suitable elements, since they are both weakly depleted and provide a reliable measure of the ratio of α-elements to Fe-group elements. In the halo stars in our Galaxy with [Fe/H] $\lesssim$ -1, this ratio clearly displays the signature of massive stars and associated nucleosynthesis in Type II supernovae. We anticipate that further observations of N, O, S, and Zn will eventually provide a better understanding of nucleosynthesis in DLA galaxies.

We thank Drs. Nino Panagia, Yichuan Pei, Max Pettini, and Donald York for helpful comments on this paper. V. P. K. acknowledges support from an AURA Postgraduate Fellowship at STScI.

REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197

Barker, E. S., Lugger, P. M., Weiler, E. J., & York, D. G. 1984, ApJ, 280, 600

Carbon, D. F., Barbuy, B., Kraft, R. P., Friel, E. D., & Suntzeff, N. B. 1987, PASP, 99, 335

Charlot, S., & Fall, S. M. 1993, ApJ, 415, 580

Fall, S. M., & Pei, Y. C. 1993, ApJ, 402, 479

Ge, J., & Bechtold, J. 1997, ApJ, 477, L1

Gratton, R. G., & Sneden, C. 1987, A&A, 178, 179

Gratton, R. G., & Sneden, C. 1988, A&A, 204, 193

Gratton, R. G., & Sneden, C. 1991, A&A, 241, 501

Green, R. F., York, D., Huang, K., Bechtold, J., Welty, D., Carlson, M., Khare, P., & Kulkarni, V. 1995, in Proc. ESO Workshop on QSO Absorption Lines, ed. G. Meylan, (Berlin: Springer), 85

Hoffman, R. D., Woosley, S. E., Fuller, G. M., & Meyer, B. S. 1996, ApJ, 460, 478

Hoffman, R. D., Woosley, S. E., & Qian, Y.-Z. 1997, ApJ, in press

Kulkarni, V. P. 1996, Ph.D. thesis, Univ. of Chicago

Lanzetta, K. M., Wolfe, A. M., & Turnshek, D. A. 1995, ApJ, 440, 435

Lauroesch, J. T., Truran, J. W., Welty, D. E., & York, D. G. 1996, PASP, 108, 641

Laird, J. B. 1985, ApJ, 289, 556

Levshakov, S. A., Chaffee, F. H., Foltz, C. B., & Black, J. H. 1992, A&A, 262, 385

Lowenthal, J. D., Hogan, C. J., Green, R. F., Woodgate, B., Caulet, A., Brown, L., & Bechtold, J. 1995, ApJ, 451, 484

Lu, L., Sargent, W. L. W., Barlow, T. A., Churchill, C. W., & Vogt, S. S. 1996, ApJS, 107, 475

Magain, P. 1989, A&A, 209, 211

McWilliam, A., Preston, G. W., Sneden, C., & Searle, L. 1995, AJ, 109, 2757

Molaro, P., D'Odorico, S., Fontana, A., Savaglio, S., & Vladilo, G. 1996, A&A, 308, 1

Morton, D. C. 1991, ApJS, 77, 119

Pei, Y. C., & Fall, S. M. 1995, ApJ, 454, 69

Pei, Y. C., Fall, S. M., & Bechtold, J. 1991, ApJ, 378, 6

Pettini, M., King, D. L., Smith, L. J., & Hunstead, R. W. 1997, ApJ, 478, 536

Pettini, M., Smith, L. J., Hunstead, R. W., & King, D. L. 1994, ApJ, 426, 79

Roth, K. C., & Blades, J. C. 1995, ApJ, 445, L95

Ryan, S. G., Norris, J. E., & Beers, T. C. 1996, ApJ, 471, 254

Ryan, S. G., Norris, J. E., & Bessell, M. S. 1991, AJ, 102, 303

Sachs, L. 1984, Applied Statistics, A Handbook of Techniques (New York: Springer-Verlag)

Savage, B. D., & Sembach, K. R. 1996, ARA&A, 34, 279

Sembach, K. R., Steidel, C. C., Macke, R. J., & Meyer, D. M. 1995, ApJ, 445, L27

Sneden, C., Gratton, R. G., & Crocker, D. A. 1991, A&A, 246, 354

Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K.L. 1996, ApJ, 462, L17

Timmes, F. X., Lauroesch, J. T., & Truran, J. W. 1995, ApJ, 451, 468

Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1995, ApJS, 98, 617

Wheeler, J. C., Sneden, C., & Truran, J. W. 1989, ARA&A, 27, 279

Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181

This manuscript was prepared with the AAS LaTeX macros v4.0.

Fig. 1.— Logarithmic gas-phase abundances relative to Zn in DLA galaxies, normalized to solar abundances (*top panel*) and halo-star abundances (*bottom panel*). The heavy filled circles and vertical bars show the medians of the observed abundances (including upper and lower limits) and the standard errors in the medians. The light vertical bars show the full range of the actual measurements (excluding upper and lower limits). Open circles show the actual measurements, and upward pointing triangles show the lower limits for elements measured in fewer than three absorbers. The lines show the expected gas-phase abundances when the intrinsic (nucleosynthetic) pattern is solar (*top panel*) or halo-star-like (*bottom panel*), and when the depletion pattern is the same as that in the warm Galactic ISM with the indicated values of the dust-to-metals ratio R/R_G.

Fig. 2.— Logarithmic gas-phase abundances relative to Fe in DLA galaxies, normalized to solar abundances (*top panel*) and halo-star abundances (*bottom panel*). All symbols have the same meaning as in Fig. 1 (with downward pointing triangles indicating upper limits).

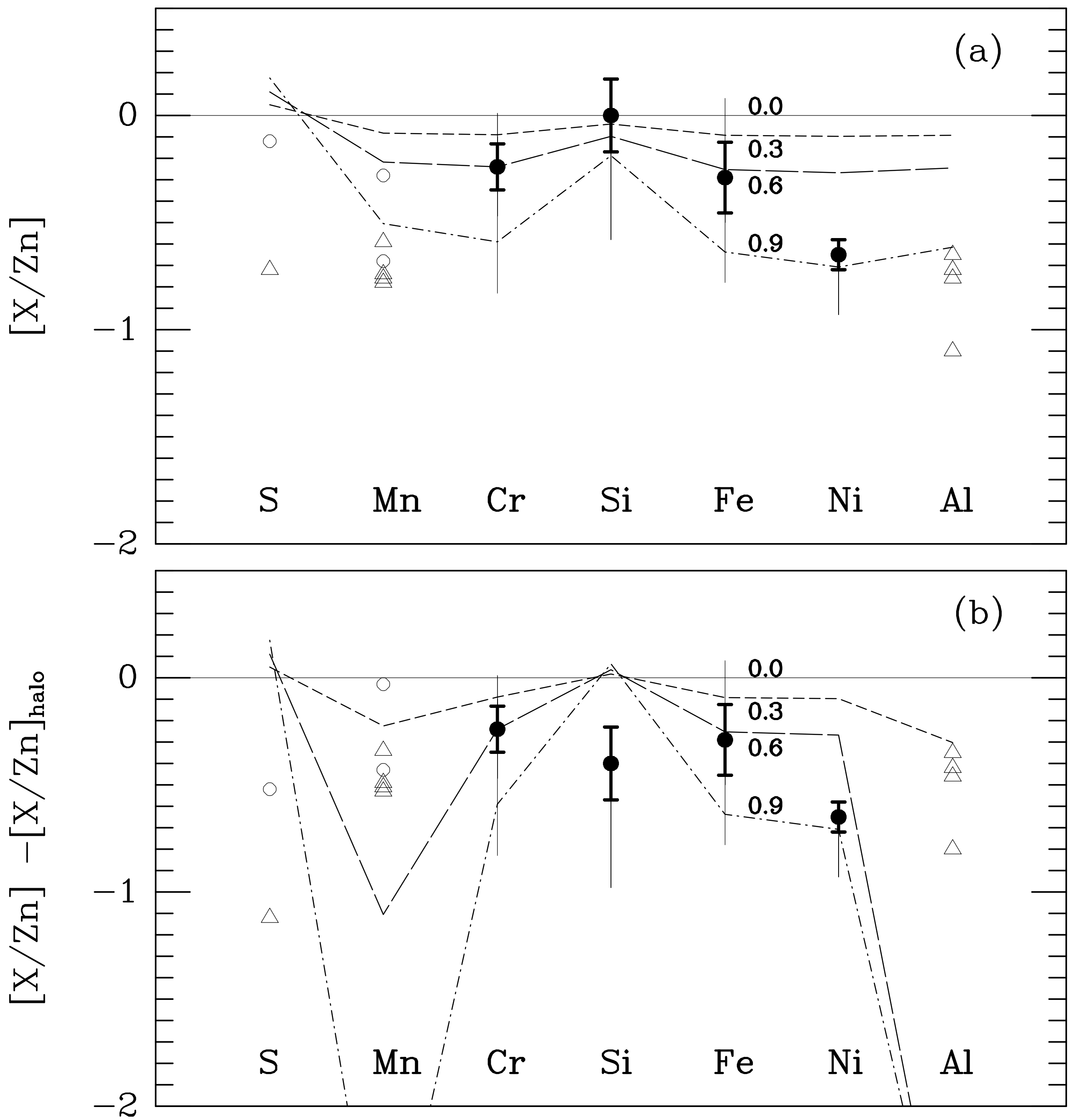

FIG. 1

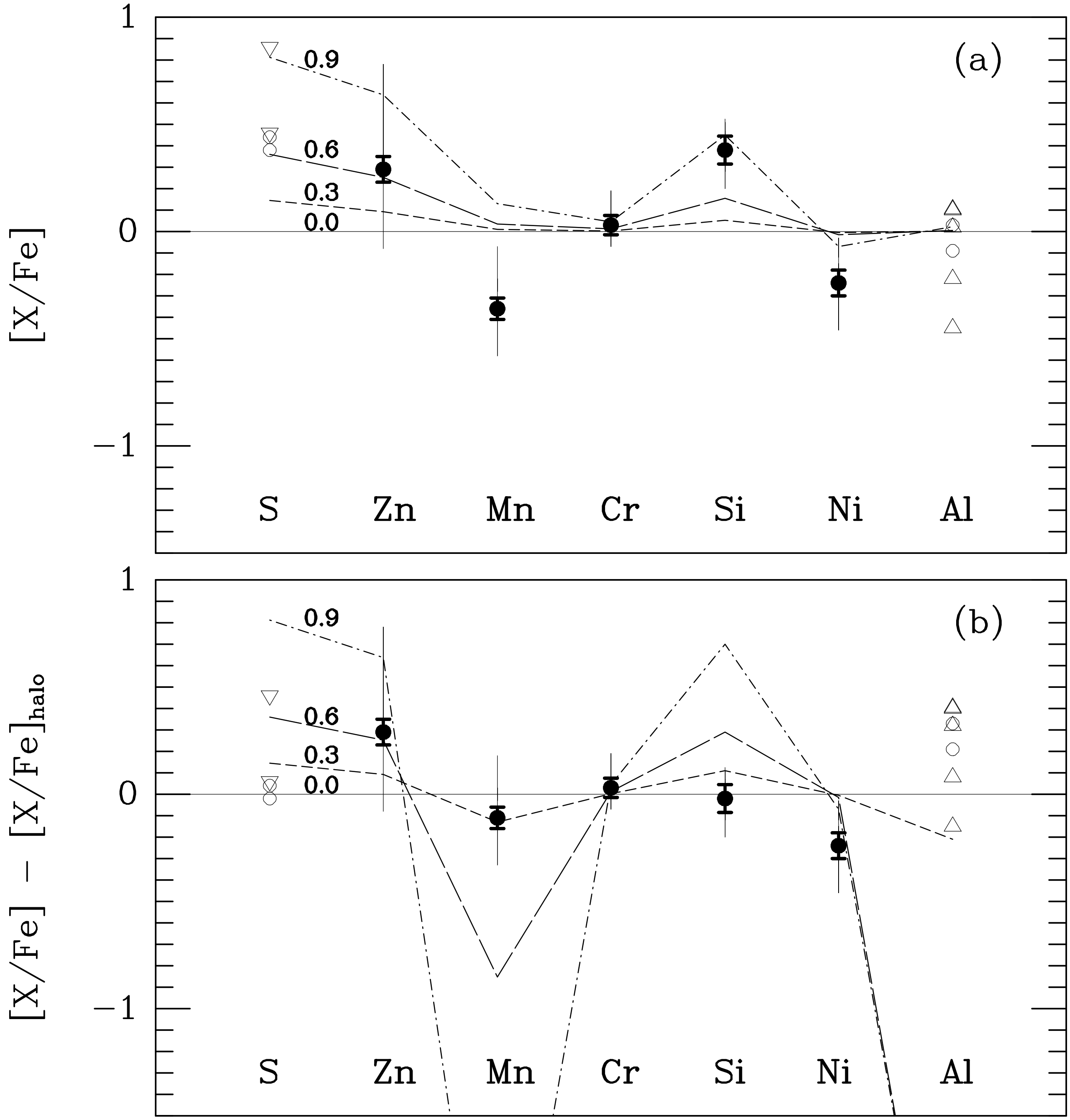
(a)
0.9
0.6
0.3
0.0
1
0
−1
[X/Fe]
S
Zn
Mn
Cr
Si
Ni
Al
(b)
0.9
0.6
0.3
0.0
1
0
−1
$[X/Fe] - [X/Fe]_{halo}$
S
Zn
Mn
Cr
Si
Ni
Al

FIG. 2